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HIGH REPETITION RATE PULSE-BURST LASER AND CAMERA
FOR ENERGY DEPOSITION RESEARCH

Final Report for AFOSR F49620-02-1-0283

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Abstract

A high speed camera and pulse-burst Nd:YAG laser system has been purchased as part of the DURIP equipment grant to be used for the development of novel diagnostic techniques and research associated with energy deposition. This system will allow a burst of laser pulses (for diagnostics and flow excitation utilizing laser energy deposition) and subsequent imaging at MHz rates. Preliminary images with the DALSTAR 64K1M camera system and two Epix frame grabbing boards have been taken for flows associated with laser induced breakdown in air and arc/plasmas plumes to test the system. The custom built pulse burst laser has been designed, assembled and initial performance evaluations completed. The laser is initiated with a Lightwave cw Nd:YAG diode pumped laser, chopped with a programmable Pockels cell Kentech pulse shaper, and amplified by five Nd:YAG flashlamp from Quantronics-Continuum. The system can provide a packet of pulses with over 28 mJ of energy with pulse separation variable from one microsecond and above. The laser and camera will be used in the study of energy deposition in supersonic flows and the development of temporally resolved flow visualization and quantitative diagnostics techniques. The techniques developed will be applied to current research projects involving energy deposition for local flow control and as well as other studies of DOD research interest.

HIGH SPEED CAMERA

The camera purchased as part of the DURIP program is a DALSTAR 64K1M which is shown in Figure 1 with components given in Table I found in the appendix of this report. The camera is controlled and images captured by two Epix D3X-64KIM PXCI frame grabber boards which are incorporated on a personal computer. The system has a framing rate up to 1 MHz with the ability to record 17 frames sequentially at 245 x 254 pixel resolution and 12-bit intensity resolution. An external TTL pulse can be used to trigger the "packet" of multiple frames which has an adjustable programmable framing rate. Although the camera has a relatively low resolution and fill factor, it will still be possible to develop the flow visualization and diagnostic techniques described below.

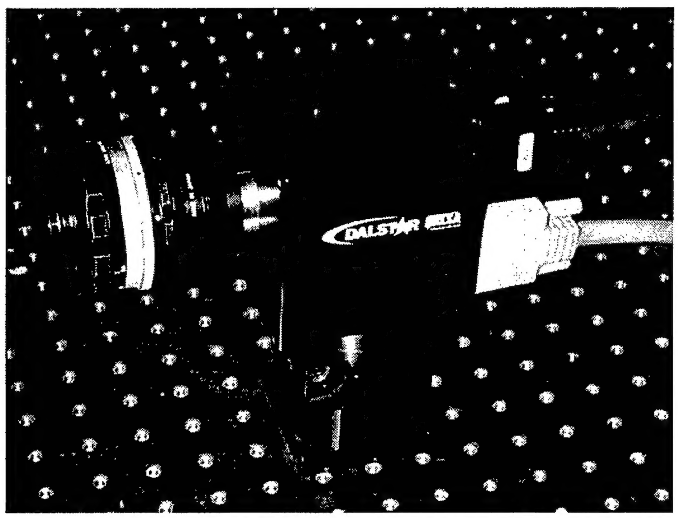


Figure 1. DALSA High speed imaging camera.

In order to test the ability to make high-speed movies associated with the on-going energy deposition research preliminary measurements were conducted using high speed schlieren photograph of the plasma and associated blast wave formed from laser induced optical breakdown of a focused 220 mJ 10 ns pulse from the second harmonic of a Nd:YAG laser. Figure 2 shows a multiple pulse schlieren movie taken of the blast wave and subsequent flow features. Due to the high framing rate of the camera the initial emission can be imaged along with the formation of the spot and blast wave at 1 μs intervals. Additionally the camera has been

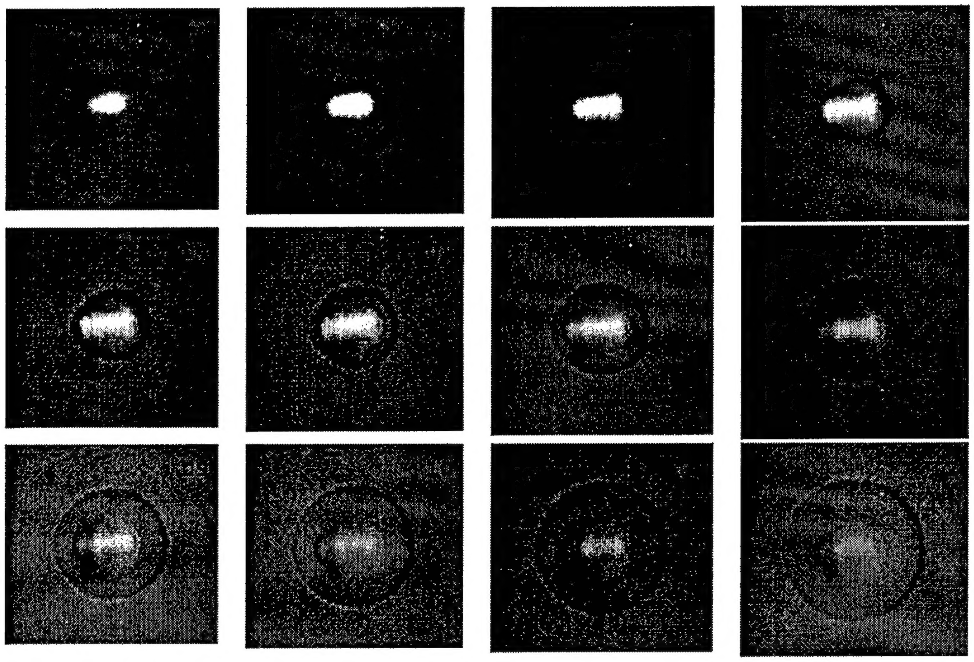


Figure 2. Evolution of laser induced breakdown from a 105 mJ Nd:YAG laser at 1 μs intervals.

utilized to image and characterize the arc/plasma created by a one micron wire which is vaporized by a high voltage power supply providing initiation voltage from 1000 to 3000 kV. This experiment allows us to control the position of the arc/plasma which could be used as an igniter or to study the effects on local energy deposition for flow control. Figure 3 shows the temporal evolution of the plasma emission created after vaporization of the wire with a 1000 kV pulse at 2 microsecond intervals taken using the DALSA high speed imaging system.

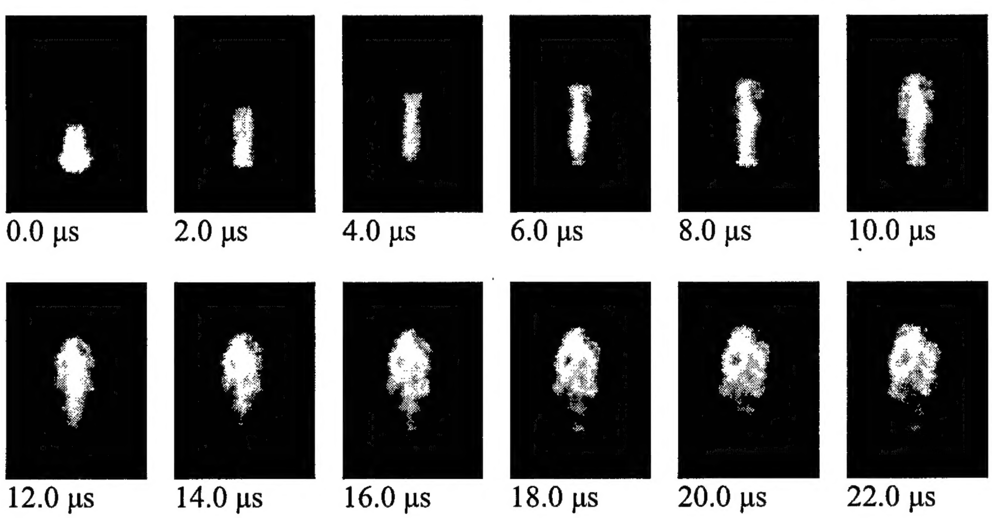


Figure 3. Plasma emission evolution of wire vaporizing under a 1000 kV pulse.

The images show the initial evolution of the plasma which first appears as a confined jet at 2 microseconds which develops into a turbulent plume as it evolves. These tests were conducted to evaluate the system and demonstrate the capabilities which will be used in future studies as described below.

PULSE-BURST LASER SYSTEM

The DURIP equipment grant provided the funds necessary to purchase equipment and components to assemble a custom made pulse-burst laser system. The components and model numbers are given in the appendix Table I. The concept of a pulse-burst Nd:YAG laser was demonstrated by Lempert et al.[1] As illustrated in Figure 4 the goal of this laser system is to reduce the power required for multiple laser pulses (as well as thermal loads on the lasing elements and optics) by providing a packet (or burst) of several (10 to 20) high repetition rate micro-pulses during a much lower burst repetition rate (on the order of 5 Hz). The basic idea behind the laser is to initiate the beam with a relatively low power cw laser, chop the intensity using a pulsed slicer and then amplify the resulting laser energy micro-pulses with several flash-lamp pumped Nd:YAG stages. The number of pulses possible for a given separation time is determined by the temporal gain curve of the Nd:YAG amplifier stages. The final system is similar to those described by Wu et al.,[2] and Thurow et al.[3] This laser system was designed, assembled, and evaluated with Dr. James Norby of Quantronix-Continuum the manufacturer of the major system components (i.e. amplifiers, cavities, and power supplies) who has built similar

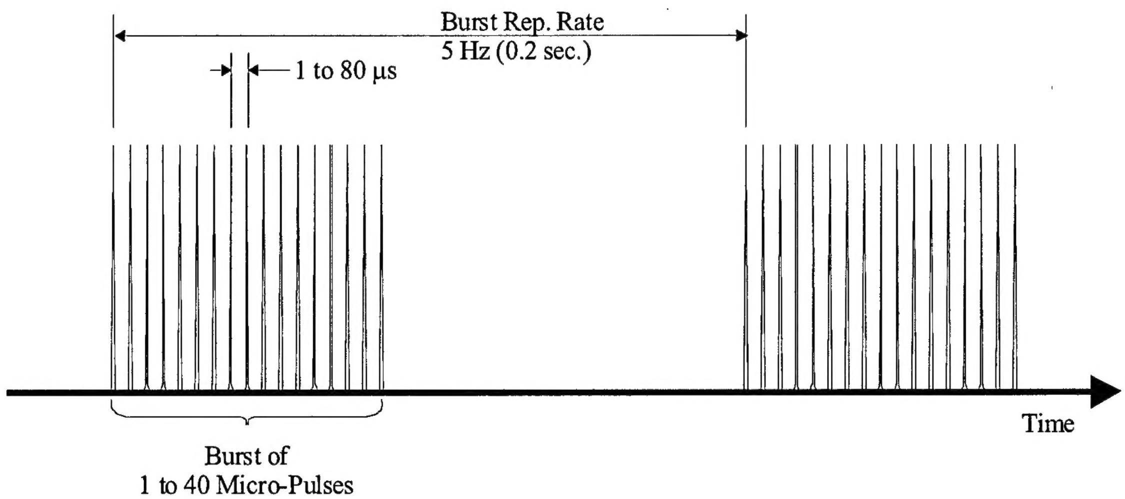
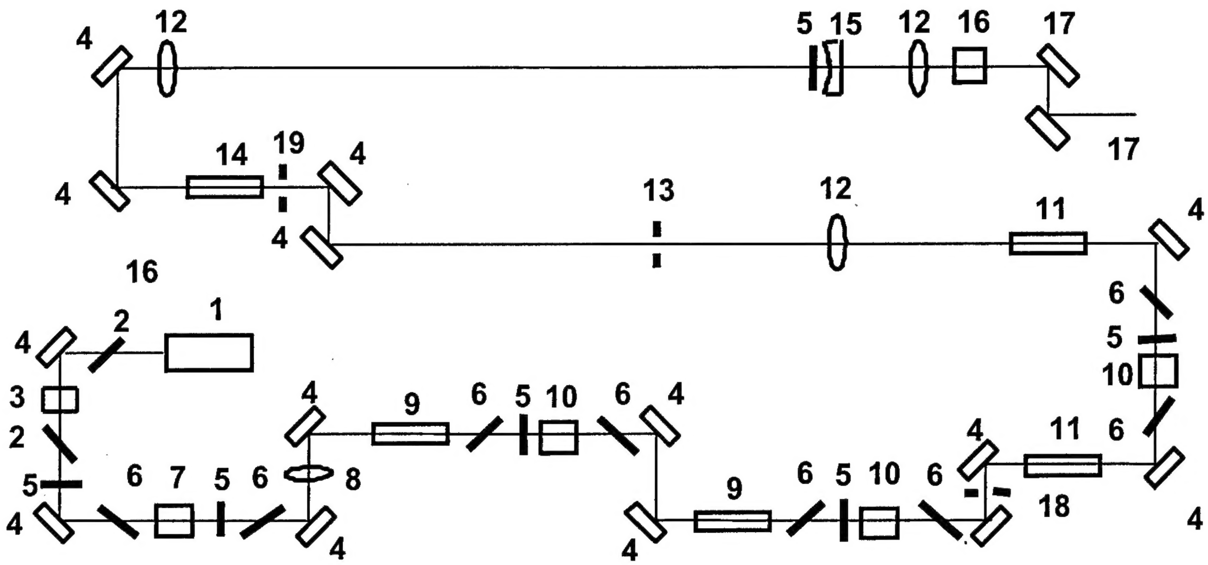


Figure 4. Schematic of pulse burst laser micro-pulses.



1. Custom, Lightwave Seeder 500mw, SLM
2. 700-0089, Polarized cube, 4FAR1064
3. Custom, Kentech Pockles cell
4. 105-0002, Mirror, Flat 25.4 1FHR 1064 45°
5. 108-0004, Wave Plate, Half 2FAR 1064
6. 199-0116, Dual Dielectric Polarizer
7. 649-0055, Faraday Rotator 4mm
8. 101-0082, Lens, +1000x15 2FAR 1064
9. 201-0094, Rod, YAG 5x115mm
10. 199-0140, Faraday Rotator 8mm
11. 201-0056, Rod, YAG ϕ6x115mm
12. 101-0204, Lens, +600x25.4 2FAR 1064
13. 314-0308, Pinhole, Ceramic 0.5mm
14. 506-0300, 9mm dual lamp amplifier
15. 102-0069, Lens cyl –7000x15mm 1064
16. 700-0049, KTP, 8x8x25mm, typeII
17. 105-0022, Mir Dic25.4 1FHR532 AR 1064 45
18. Custom, Apodizer, 5mm
19. Custom, Apodizer, 8.5mm

Figure 5. Schematic of final pulse-burst laser system.

laser systems previously. Since these are the same type of amplifiers utilized in single-pulse Nd:YAG lasers they can be easily serviced in the future and replace if they are damaged. Additionally the pulse burst laser system design and component selections were greatly enhanced by interactions with Dr. Walter Lempert and Brian Thurrow of The Ohio State University and Dr. Mark Wernet from NASA Glenn research center.

Figure 5 shows a schematic of the final pulse burst laser system giving the major components used in the construction. The laser is initiated by a continuous wave diode pumped non-planar ring laser (Lightwave 126-1064-500) that serves as the primary oscillator providing 500 mW of power at a wavelength of 1064. The laser can be tuned in frequency by adjusting the

operating temperature (providing slow frequency tuning) and a higher response time frequency change (over 30 kHz) is possible by stressing the piezoelectric transducer which is attached to the crystal. The beam is then chopped into a multi-pulses beam with a programmable Kentech Pockels cell pulse shaper. Over the 100 μs gain curve of the amplifiers a succession of ~30 ns packets can be programmed for position and transmission amplitude. This allows control of the energy distribution that will be introduced to the amplification stages so that not only the frequency of the micro-pulse packet can be controlled, but also the amplitude can be adjusted for each pulse independently so that the entire pulse train can have a more uniform energy distribution over all micro-pulses. Note that the transmission profile over the gain curve must be adjusted as the frequency of the multiple pulses is modified by a text file download to the pulse shaper through a computer controlled RS232 serial input. The pulse shaper was also temperature stabilized which greatly reduced the pulse to pulse energy variation. The train of pulses is then amplified by 5 Nd:YAG amplifier stages with optical Faraday isolators to prevent feed back and appropriate lenses to control the beam diameter and divergence. A KTP crystal doubles the frequency resulting in a wavelength of 532 nm. Figure 6 shows the custom built laser system as described above.

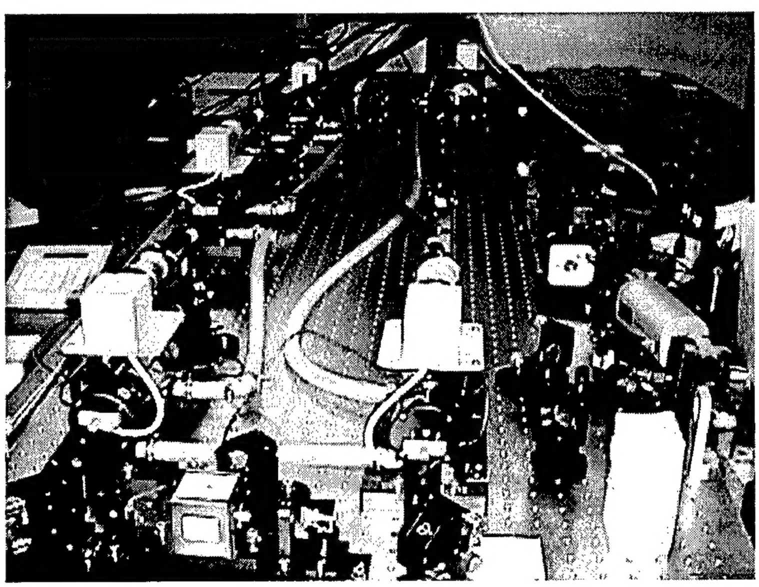


Figure 6. Custom built pulse-burst laser.

Table 1. Initial pulse-burst laser performance levels.

Micro-Pulse Separation [μs]	2	4	8	16
Number of Micro- Pulses	20	20	11	6
Power of Beam at 532 nm [W]	2.85	2.75	1.8	1.0
Energy of Single Micro-Pulse	28	28	33	33

Measurements have been made to quantify the performance of the pulse-burst laser system. Table 1 gives the energy levels and number of micro-pulses in pulse train for varying pulse separation times. As expected as the pulse separation time increases the number of pulses which can fit into the amplifier gain curve decreases while the energy per pulse increases. Figure 7 shows oscilloscope traces for each of these pulse separations quantified with Figure 8 showing an individual micro-pulse temporal profile. Although there appears to be some micro-pulse variation in amplitude this is due in part to the resolution of the oscilloscope and can be improved with further adjustment to the programmable pulse shaper profile. The individual temporal profile is shown to be Gaussian as expected in a single mode laser pulse which is necessary for some of the purposed diagnostics which will be developed in the future. The FWHM of the micro-pulses is measured to be 16 ns after frequency doubling. The shot to shot stability over 1000 pulses was measured to have an energy standard deviation of 1%. The spatial beam profile is found to be within 70% Gaussian in the near field with a beam diameter of 5.1 mm and over 92% Gaussian in the far field. This laser has a sufficient performance to be utilized in the diagnostics and laser induced energy deposition studies which will be conducted in the future. It should be noted that as more experience is gained in using the laser increased performance is expected.

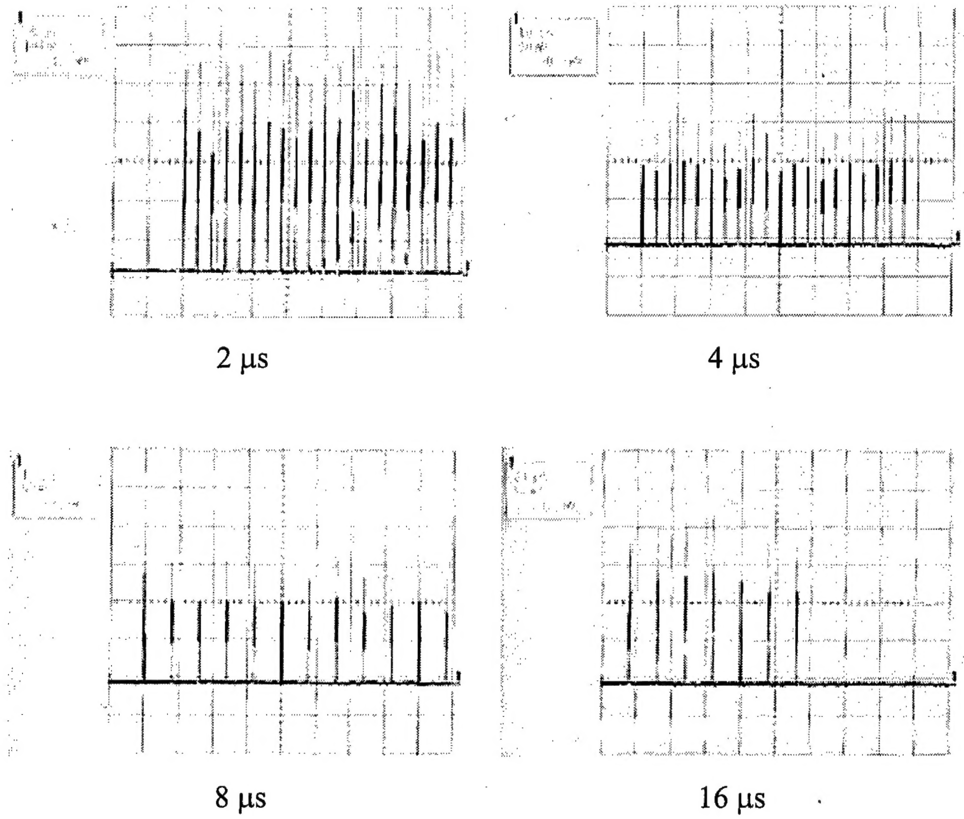


Figure 7. Oscilloscope traces of micro-pulses from pulse-burst laser.

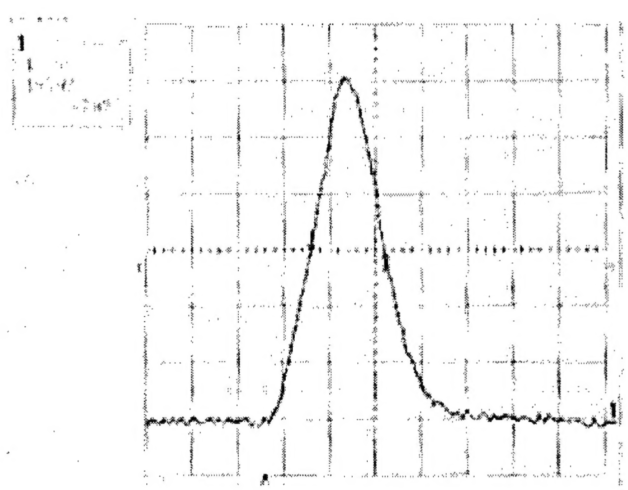


Figure 8. Oscilloscope trace of single micro-pulse.

FUTURE INVESTIGATIONS

After further experiments are conducted to quantify and document the pulse-burst laser system performance there are two research avenues which will be investigated related to current research interests of AFOSR and DOD. One of the goals of the purchased equipment is to develop and apply diagnostics which are temporally resolved. After additional optimization of the laser is completed we plan to investigate the development of temporally resolved flow visualization techniques including laser sheet lighting and schlieren based flow visualization techniques. One of the difficulties when utilizing schlieren photography is providing a light source which has a short duration, uniformity, and small temporal jitter. This is particularly difficult when high speed frames are desired where the exposure time is determined by the camera. By focusing the beam from the pulse-burst laser to a spot in an encapsulated gas (argon in our case) a laser induced spark is created ionize giving off photons in the familiar bremsstrahlung process. This becomes an effective light source for schlieren since it has high intensity, short pulse duration and excellent uniformity. Although air environments in the flow have been used previously by others,[4] by using an argon environment the uniformity and intensity of the resulting spot are increased significantly. The laser spark source gives a much improved image of the flow and shock detail due not only to the decreased exposure time of the flash, but also due to the increased intensity which allows additional filters to be used to reduce the emission from the flow field being observed. Previously we have utilized this technique to measure the phase-averaged effect of energy deposition in high speed flows. Now with the pulse-burst laser we will be able to resolve the temporal evolution of a single breakdown process and characterize the evolution of the details which were obscured by previously by phase averaging.

Additionally temporally resolved quantitative techniques can be investigated. This includes the development of velocimetry techniques utilizing the camera and pulse-burst laser system such as Particle Image Velocimetry (PIV)[5] and Planar Doppler Velocimetry (PDV).[6] Both techniques illuminate the seeded flow field by spreading the light from the pulse-burst laser into a two dimensional sheet. PIV tracks particles seeded into the flow from one frame to the next using space correlation techniques to find the particle displacement and, with knowledge of the laser pulse separation times between frames, the velocity can be calculated. It should be noted however that the current camera system has a slightly low resolution for PIV which may

limit the field-of-view possible. Alternatively PDV utilizes scattering from a volume of much smaller particles measuring the Doppler shift frequency (which can be related to the Doppler shift) utilizing an iodine absorption filter. This technique is possible since the pulse-burst laser by design has a narrow spectral linewidth and can be tuned to the absorption lines of iodine.[7] PDV offers two advantages over PIV; 1) smaller particles can be utilized that better track features (i.e. turbulent structures and shocks) of high speed flows and 2) PDV does not require imaging of individual particles making it more suitable to lower resolution cameras. It should be noted that since multiple frames of velocity are obtained with PIV or PDV, acceleration terms can also be evaluated in high speed flows. Both of these velocimetry techniques will be investigated and utilized in the investigations which are being conducted in the gas dynamics laboratory on compressible flow and laser induced optical breakdown for local flow control to provide information not previously possible. Additionally the development of temporally property measurement techniques can be investigated utilizing molecular filtered based diagnostics (Filtered Rayleigh Scattering) and single-shot Raman spectroscopy. The current camera system may not have the sensitivity needed for these molecular scattering techniques, but research partners at UIUC have line scan cameras with the appropriate resolution and sensitivity that can be utilized to develop these techniques for point measurements.

Once the pulse-burst laser arrives research will begin to extend the diagnostics described above to temporally resolved measurements and apply them to the energy deposition flow fields studied. The flow fields investigated will focus on high speed flows such as shear layers, base flows, and wall bounded flows where the high repetition rate is needed to characterize the evolution of flow phenomena. The emphasis of the high speed flow investigations which will utilize the high speed camera and pulse burst laser, however, will focus on investigations utilizing energy deposition for local flow control. These flows include the control of resonant pressure fluctuations in supersonic flow past an open cavity, control of sock wave turbulent boundary layer interactions, and control of shock-vortex interaction and vortex breakdown. The pulse burst laser system will not only be used in the temporally resolved diagnostic techniques described above to investigate these flows, but also the use of the laser as a multi-pulse laser induced optical breakdown source will be investigated. This will open new possibilities to determine if a high repetition rate pulse can reduce the energy required in high speed flows to observe gains shown to exist by continuous wave lasers. Additionally we now have the

capability to investigate if most amplified frequencies can be excited in high speed flows (which can be on the order of 10 to 100 kHz) and determine how multiple pulses can be utilized to initiate breakdown which can be sustained with microwaves. It should be noted that this only represents a brief description of the multiple investigations which can be conducted in the future utilizing the high speed camera and pulse burst laser purchased as part of the DURIP program.

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[6] G.S. Elliott, and T.J. Beutner, "Molecular filter based planar Doppler velocimetry," Invited article for *Progress in Aerospace Sciences*, 35: 799-845, 1999.

[7] Thurow, B., Hileman, J., Samimy, M., and Lempert, W., "Progress Towards Real-Time Planar Doppler Velocimetry," AIAA Paper No. 2003-0916, January, 2003.

APPENDIX

Table I. Components of High Speed Camera and Pulse-Burst Laser System

High-Speed Framing Rate Camera

Company	Item (Components Listed)	DURIP Funds
DALSA	DALSA SMD-64K1M Camera - 64K1M C-Mt Masked (DS-41-64K1M) - Power Supply and Cable (24-00001-02) - ENG-CA REM 9 Pin Connector (31-00004-10)	$ 34,239.00
Epix Inc.	Frame grabbing board - PCI interface for DALSA Camera (D3X-64KIM) - Data Cable (CBL-D32-64KIMT-3M) - Data Cable (CBL-D32-64KIMT-3M) - Camera Control Cable (CBL-RS232-SMD-3M) - Module (TTL-Module)	$ 4,840.00
	Camera Control Imaging Program -XCAP-Std	$1,495.00

Pulse-Burst Laser System

Company	Item (Components Listed)	DURIP Funds
Lightwave Electronics	Diode Pumped Nd:YAG cw Laser - CW NPRO Laser 500 mW @1064 (126-1064-500) - Power Supply (125/6-OPN-PS)	$ 14,800.00
Quantronix-Continuum	Multiple Pulse Amplifier System with Pulse Slicer - Kentech Pockeles Cell Pulse Shaper (700-095) - Pulse Shaper Driver (J0308271) - 4 mm Faraday Rotator Optical Isolator (649-0055) - 3 x 8 mm Faraday Rotator Optical Isolator (199-0140) - 2 x 5 mm Amplifier Heads (811U-05) - 2 x 6 mm Amplifier Heads (811U-06) - 1 x 9 mm Amplifier Head (812V-09) - 2 x 5 mm Nd:YAG Rods (YAG VLOC 201-0094) - 2 x 6 mm Nd:YAG Rods (YAG VLOC 201-0056) - 1 x 9 mm Nd:YAG Rod (YAG VLOC 506-0300) - Ceramic Spatial Filter (314-0308) - KTP SHG Crystal 8x8x25 type II (700-0049) - Capacitor Banks and Power Supply/Control Unit - Optics (mirrors, lens, polarizers, waveplates, apodizers) - Optical mounts and breadboard	$180,850.00
	Total	$ 236,224.00